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LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Life cycle assessment of advertising folders

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Abstract
Purpose Pulp and paper manufacturing constitutes one of the largest industry segments in term of water and energy usage and total discharges to the environment. More than many other industries, however, this industry plays a key role in sustainable development because its most important raw material, wood fiber, is renewable Dias and Houtman (Environ Prog 23(4):347–357, 2004). Actually, even if the communication is dominated by electronic media, paper-based communication has a role to play due to its unique practical and aesthetic qualities. This research aims to assess the environmental impact of advertising folders produced with different papers and distributed by a system of Italian consumers' cooperatives in order to indicate the possible options of improvement and to assess the $CO_{2\ (eq)}$ emitted during the entire life cycle.
Methods Life cycle assessment (LCA) was performed from cradle-to-grave considering paper production, transport from paper mill to printing site, printing, distribution, and disposal. Data for the study were directly collected from specific companies and completed on the basis of literature information. The analysis was conducted using the SimaPro 7.1.5 software and IMPACT 2002+ method to assess all its environmental impact and damage categories.
Results and discussion LCA analysis indicates that the higher environmental impact is mainly due to paper production and printing processes. The main operations which generate the major impact in the paper production stage are related to the direct or indirect fossil energy use, the production of additives for bleaching operations, and the collection and selection of waste paper. Printing causes relevant impacts for the electricity and ink production and for the aluminum plates used in the offset printing. Moreover, the use of paper with low quantity of additives and small amount of primary fibers causes a reduction of the environmental load of 13.94%. The major global warming potential value was found for advertising folders made with little amount of mechanical pulp which slightly contributes to the absorption of CO_2.
Conclusions The analysis pointed out the relevance of the paper production phase and of the printing step within the advertising folders life cycle and allowed to detect the other critical stages of the life cycle. Paper composition greatly affects the environmental impact of the advertising folders' life cycle.

Keywords Advertising folder · Carbon offset · Global warming potential · LCA · Paper

1 Introduction

Paper is a really an old material, known since the fifth century. Nowadays, it has several applications such as writing, printing, packaging, and cleaning. Though it was always considered as the most ecological material because it is composed of wood,

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water, and some additives, in recent years, paper was the target of negative and often misinformed environmental criticism. Beside the deforestation problem, paper manufacturing process involves relevant energy consumption and overflowing landfill sites (Gaudreault et al. 2010). Energy decision making in a pulp and paper mill involves selection of LCA system boundary. Nevertheless, paper is also one of the few truly renewable resources. In fact, papermaking and other industries that depend on trees guarantee that the world's forests used to make paper products are responsibly managed by planting trees to balance the timber harvested (Paquette et al. 2009).

Despite the growing reliance on business technology and electronic communication, paper-based communication continues to have a key role to play when developing a marketing strategy. In recent years, Coop, a system of Italian consumers' cooperatives which operates the largest supermarket chain in Italy, has promoted some sustainable campaigns, for example to improve the use of tap water or to decrease the use of unrecyclable plastic containers. The last environmental challenge launched by Coop concerned on the environmental load assessment of the advertising folders delivered to the consumers for communicating sales offers. Printed communication uses paper as its primary material that besides binders and fillers is mainly constituted by different amount of primary (mechanical or chemical pulp) and recycled fibers with respect to the final destination. Generally, it is not possible to produce a paper without primary fibers because every time a fiber is recycled, it shortens itself more and more. In fact, it is possible to recycle a fiber no more than four or five times, in order to ensure a good paper resistance.

The pulping industry traditionally uses mechanical or chemical pulping methods, or a combination of the two, to produce pulps of desired characteristics. The mechanical processes, which account for about 25% of the wood pulp production in the world today, are constituted by several high-energy grinding and refining systems, including refiner mechanical, thermomechanical, chemimechanical, and chemithermomechanical pulping processes (Sundholm 1999).

The chemical pulping method, which supplies 75% of world's wood pulp, traditionally uses the kraft, or sulfate, process. Even if this method produces paper with higher strength compared with that produced by mechanical pulping, it has the disadvantages of being capital- and energy-intensive, giving relatively low yields, producing troublesome waste products, and producing by products that are of relatively low values (Smook 1992).

In this study, life cycle assessment (LCA) methodology was used to quantify the environmental impact caused by a biweekly production of advertising folders obtained with a paper containing 74% of recycled fibers, 2% of mechanical pulp, 5% of humidity, and 19% of pigments and fillers (paper A). LCA was performed from cradle-to-grave considering paper production, transport from paper mill to printing site, printing, distribution, and disposal. The analysis was conducted using the SimaPro 7.1.5 software and IMPACT 2002+ method (Jolliet et al. 2003) to assess the environmental impacts. In order to evaluate the effect on the environmental load of using paper with different recycled content, a comparison with two different types of papers, papers B and C, was performed. Finally, the attention was focused on the calculation of the mass of greenhouse gases (GHGs), expressed as CO_2-equivalents, emitted during the entire life cycle, in order to quantify the number of trees to be replaced for offsetting emissions (Boguski 2010).

The Kyoto Protocol recognizes forestry and land use change activities as sinks and sources of atmospheric carbon. The Intergovernmental Panel on Climate Change (IPCC) claims that activities related to land use change and forestry contribute to reducing greenhouse gas emissions by avoiding deforestation or improving forest management (Yong Shin et al. 2007; Smith 2002). All papers used for this study belong to certified forest that means that for every tree that is logged in managed forests, a new one is replanted. In this study, a preliminary quantification of the number of trees to be replaced for offsetting the mass of GHG emitted during the entire life cycle of advertising folders was performed.

2 Methods and assumptions

2.1 Goal and scope definition

The aims of this LCA study were:

- To assess the environmental impacts of a biweekly production of advertising folders over their entire life cycle in order to identify the stages with the largest environmental load (hot spots)
- To compare the effect on the environmental impact of using different papers that mainly differ for percentages of mechanical and recycled pulp
- To determine the mass of GHG, expressed as CO_2-equivalents, emitted during the entire life cycle, in order to quantify the number of trees to be replaced for offsetting emissions

2.2 Functional unit and system boundaries

Every 2 weeks, Coop prints 182,200 copies for communicating sales offers to the consumers. The functional unit was defined as the weight of a biweekly production of advertising folders constituted by 24 colored double-sided pages with an area of 0.0549 m^2 and grammage of 49 g/m^2 (11.700 kg). The paper used for the present

study (paper A) contains 74% of recycled fibers, 2% of mechanical pulp, 19% of binders and fillers, and 5% of humidity. The system boundaries for the analysis were not restricted to the printing process, but, following the LCA approach, included also the upstream and downstream phases. The entire life cycle, shown in Fig. 1, was composed of the following stages:

- Paper production (includes forestry, recycled fiber production, and pulp production)
- Paper distribution from the paper mill to the printing site
- Printing
- Final distribution (includes transports from the printing site to distribution centers) and disposal (supposed to be equally split up in recycling, incinerating, and landfilling)

Besides these main sequential processes, each stage also includes additional processes, such as transport, chemical production, energy and fuel production, and processes which were added to the system boundaries to avoid allocation. In order to simplify the study, the materials that represent less than 1% (in mass) of the functional unit were left out except for the chemical additives used in the pulp production processes that are energy-intensive items. The production, maintenance, and disposal of buildings and machinery as well as the environmental burdens related to the production of inks, silicon, packaging, and other auxiliary materials were also included in the present study. Non-material values, costs, and human resources were not considered.

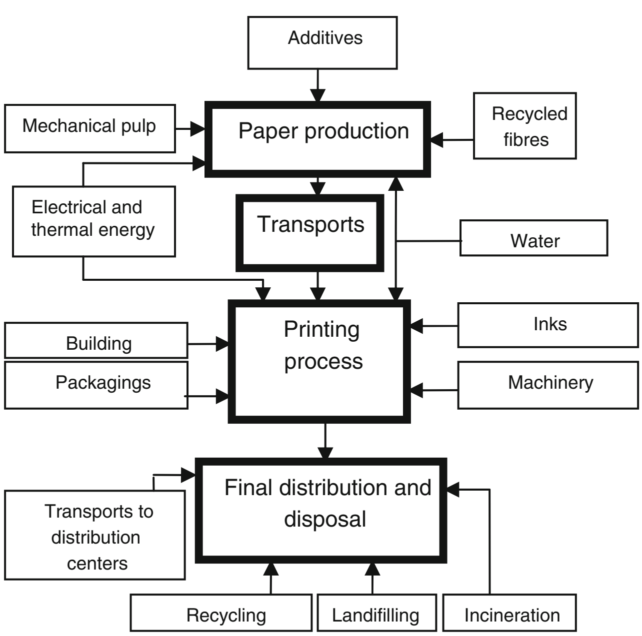

Fig. 1 Advertising folders' life cycle

The functional unit used for the comparison of the different papers was 1 kg, while the functional unit to compare the biweekly production of advertising folders produced with the different papers was the weight of the 24 colored double-sided pages with an area of 0.0549 m^2.

2.3 Life cycle inventory

The compilation of inventory data was carried out using databases included in SimaPro 7.1.5 software. Whenever possible and feasible, average or typical process-specific data were collected. The remaining data were obtained from specialized databases and literature. Primary data obtained in cooperation with some representative companies for the year 2009 were used to gather information about the inputs (i.e., materials, water, and energy resources) and outputs (i.e., airborne and waterborne emissions and solid waste) for the considered processes. To model the paper production stage, both primary and secondary data were used. In particular, the amount of the paper components such as mechanical and recycled pulp, water, fillers, and binders were provided by paper industry, while secondary data obtained from the Ecoinvent database (Life Cycle 2009) were used to model the background processes (land use, materials production, fuel and electricity production, transport, and machinery operations). In the paper production stage, recycled and mechanical fibers are collected and manufactured. The recycled ones are deinked with chemical components and then dissolved in water solution. Primary fibers are chipped, bleached, and dissolved in water solution. Chemicals components are successively added to the mixture of mechanical and deinked fibers and the final solution is then filtered and dried. The humidity content has to be 5–10% for packing paper reels. A selection of important data used in the paper production stage is reported in Table 1.

The Ecoinvent process (*paper, recycling, with deinking)* used to model the paper production stage does not include primary fibers (Werner et al. 2007; Hischier 2007). Consequently, the Ecoinvent process was modified by the addition of thermomechanical pulp in order to consider the small amount of mechanical pulp present in paper A. In agreement with European data (Lopes et al. 2003), softwood was used as raw material to produce the mechanical pulp and data on its production were taken from Ecoinvent database. Infrastructures and land use were based on 50 years of service considering a pulp production of 400 kt/year. Data for transport, printing, and final distribution were directly collected from the companies whenever possible and finally integrated with the Ecoinvent database information. After the production, paper is transported to the printing site. Transport distances were given from paper producers, considering that paper reels were freight to the printing site by rail (5,627.180 tkm) and by road (2,201.940 tkm). Transport

Table 1 Inventory data for the paper production process

	Category	Components	Quantity	Source of data
Input	Wood	Mechanical pulp	0.0367 kg	Straight from the company
	Waste paper	Recycled fibers	1.174 kg	Straight from the company
	Water	Water, in ground	0.017 m^3	Straight from the company
	Fillers	Kaolin	0.0992 kg	Straight from the company
		Potato starch	0.0519 kg	Straight from the company
	Unbleaching materials	Sodium hydroxide	0.0157 kg	Straight from the company
		Hydrogen peroxide	0.0211 kg	Straight from the company
		Sodium silicate	0.0125 kg	Straight from the company
	Binders	Aluminum sulfate	0.0159 kg	Straight from the company
		Rosin size	0.0245 kg	Straight from the company
	Other chemical components	Chemicals inorganic	0.0074 kg	Straight from the company
	Transport	Road Rail	0.0248 tkm 0.149 tkm	Transport processes I/O data derived from Ecoinvent database. Transport distances were supplied by the paper company and it was considered that wood was transported, on average, for 100 km
	Energy input	Electricity Fuel oil	0.79 kWh 1.312 MJ	Energetic processes I/O data derived from Ecoinvent database. Energy demands were estimated from literature
		Natural gas	6.78 MJ	
		Hard coal	1.55 MJ	
	Auxiliary process	Integrated paper mill	5.44E-11 unit	Integrated paper mill data were derived from Ecoinvent processes
Output	Emissions to air Emissions to water	Heat AOX	2.84 MJ 9.67E-6 kg	No other emissions to air were reported as they are already considered in the fuel combustion for heat production. Emission to water data were derived from Ecoinvent processes
		BOD5	0.00041 kg	
		COD	0.00342 kg	
		TOC	0.0105 kg	
		N (as N)	0.00021 kg	
		P (as P)	3.06E-6 kg	
		Suspended solids	0.00125 kg	
	Waste to treatment	Disposal to landfill Disposal to incineration	0.14299 kg 0.007144 kg	Waste treatments were derived from Ecoinvent processes. Transport to disposal plants was considered too
		Disposal to underground deposit	0.00012 kg	

processes I/O data were derived from the Ecoinvent database. Paper reels delivered to the printing site are unpacked and covered with silicon in order to let the inks to bond to the surface. The obtained advertising folders are cut, folded, and packed with polypropylene. Finally, they are transported to the distribution centers. Table 2 shows some of the most relevant data used in the printing process. Auxiliary processes such as inks, aluminum, and natural rubber plates were created using primary data and Ecoinvent database.

Compositions, quantities, and transport distances were given directly by the producers, while their production and disposal I/O data were obtained from the Ecoinvent database. The advertising folders are then transported to the distribution center (2,412 tkm) and finally disposed. Regarding the disposal scenario, the information was directly supplied by the national consortium for the recovery and recycling of cellulose-based packaging. Waste paper is recycled (33.3%), landfilled (33.3%), and incinerated (33.3%) and waste treatments were derived from Ecoinvent processes.

2.4 Impact assessment

Life cycle impact assessment (LCIA) results were generated with IMPACT 2002+ method using Simapro 7.1.5, to determine the environmental impacts related to the emissions released and resources consumed in the system under study

Table 2 Inventory data for the printing process

Category	Components	Quantity	Source of data
Materials	Kraft paper	20 kg	Straight from the company
	Core board	32 kg	Straight from the company
	Silicon	27 kg	Straight from the company
Transports	Road	4.590 tkm	Transport processes I/O data derived from Ecoinvent database. Silicon supplier distances were furnished directly from the company
	Forklift	4.375 tkm	Straight from the company. The forklift process was created using Ecoinvent database information
Energy input	Electricity Natural gas	3,435.2 kWh 2,062.38 MJ	Energetic processes I/O data derived from the printing company
Water	Water, decarbonized Water, deionized	6 t 0.5 t	Water data used by cooling towers and roto offset print was supplied by the company
Auxiliary process	Printing building Roto offset printer Filters	3.7525E-6 unit 3.7525E-6 unit 0.065 unit	Straight from the company. For the building, both occupation area and materials were considered. For the printer, materials and manufacturing of the machinery were considered
Emissions to air	Particulates<2.5 µm NO_x VOC SO_x	24.174 g 1,118.073 g 683.628 g 45.254 g	Straight from the company
Waste to treatment	Waste paper for further treatment	−582 kg	Disposal scenario was given from the producers while waste treatment was derived from Ecoinvent process. Waste paper was considered as avoided product in the paper production

(Jolliet et al. 2003). This impact assessment method covers midpoint and endpoint analysis with equal weighting values for all damage categories. In addition, it includes many substances and the most important impact categories with respect other methods (Goedkoop and Spriensma 2001; Potting and Hauschild 2004; Steen 2000), but the following additions and modifications were done to be more representative of the considered system:

– Global warming potential (GWP) was also characterized using the more commonly recognized factors from the International Panel on Climate Change for a 100-year time horizon (IPCC 2003). This allows the potential effect on climate change from different activities to be evaluated on a common basis.
– Land use was estimated using basic indicators of both land occupation and transformation. In the present study, *transformation to forest intensive*, *normal*, *transformation to forest intensive*, *and transformation to arable* were introduced.
– Mineral extraction was characterized considering some additional resources such as silver, gravel, sand, lithium, bromine, and water in ground derived from the category Minerals of Eco-indicator 99 with the same characterization factors.

3 Results and discussion

3.1 Inventory analysis results

Firstly, an interpretation on the basis of midpoint categories was conducted being more appropriate to evaluate the environmental impacts of the different substances counted in the life cycle inventory. Finally, in order to cross-compare the shares of the individual impact categories with reference to the damage categories, the impact assessment was also discussed at the endpoint level. The impact categories included in this study are reported in Table 3 with respect to the life cycle phases included in the study.

The analysis of the results at the midpoint level highlights that the paper production stage plays the major role in all the impact assessment categories. Most of global warming potential results primarily from paper production which contributes for more than 50% and secondarily from the distribution and disposal process for about 36%. The most relevant contribution to this potential impact is mainly due to CO_2 emissions belonging to the combustion process of the natural gas employed in the paper production and in particular in the recycling with deinking step. Regarding the final disposal stage, the contribution is due to CO_2 emissions from incineration. The GWP result obtained with IMPACT 2002+ is significantly lower than

Table 3 Characterized LCIA results

Impact category	Unit	Total	Paper production (%)	Transport (%)	Printing (%)	Final distribution and disposal (%)
Nonrenewable energy	MJ primary	404,727.23	78.95	2.52	16.33	2.20
Eutrophication potential	kg $PO_{4\ (eq)}$	2.34	78.65	1.27	11.19	8.89
Carcinogens	kg $C_2H_3Cl_{\ (eq)}$	392.7	64.76	1.33	18.73	15.18
Noncarcinogens	kg $C_2H_3Cl_{\ (eq)}$	687.13	48.24	0.91	6.29	44.55
Respiratory inorganics	kg $PM_{2.5\ (eq)}$	19.28	73.77	4.97	16.41	4.86
Respiratory organics	kg $C_2H_{4\ (eq)}$	7.21	69.27	4.38	20.75	5.59
Mineral extraction	MJ surplus	355.34	65.02	2.9	30.99	1.09
Ionizing radiation	Bq C-14 $_{(eq)}$	674,261.70	85.98	2.34	9.98	1.70
Ozone layer depletion	kg CFC-11 $_{(eq)}$	0.01	73.5	3.29	19.84	33.66
Aquatic acidification	kg $SO_{2\ (eq)}$	99.58	74.62	3.57	16.73	5.07
Terrestrial acidification	kg $SO_{2(eq)}$	373.03	71.04	5.73	15.59	7.63
Aquatic ecotoxicity	kg TEG_{water}	1,694,266.4	69.09	2.06	14.27	14.59
Terrestrial ecotoxicity	kg TEG_{soil}	636,756.87	79.91	2.94	13.04	4.12
Land occupation	m^2org·arable	1,885.68	80.40	0.47	18.51	0.62
Global warming	kg $CO_{2\ (eq)}$	22,390	80.82	2.58	14.61	1.98
Global warming potential[a]	kg $CO_{2\ (eq)}$	30,952	52.69	1.88	9.51	35.92

[a] IPCC 100 years

the one calculated with IPCC because the emissions of biogenic carbon dioxide, biogenic methane, and carbon dioxide in air are not considered. Paper production is the subsystem affecting most the nonrenewable resource depletion. The key energy-consuming operation is the paper recycling with deinking which consumes, in fact, exclusively nonrenewable fuels such as natural gas, heavy fuel oil, and coal whose extraction is responsible of the largest contributions. The second contribution to this impact category is that of printing because it comes from the electricity used for capital goods. Even though the transport of wood to mills (80% by road and 20% by rail) is intensive as well as the paper delivery to the printing industry, the energy use in transport and in disposal was insignificant. The respiratory inorganic effects, dominated by particle emissions to soil as well as secondary particle creating emissions of NO_x and SO_2 to air, represent the major impacting sources in the paper production stage. The production of energy (on-site and in the national grid) and the fuel combustion in the pulp production process account for 33.7% of particulates, 33.7% of NO_x, and 22.6% of SO_2 emissions. For respiratory organics, the recycling with deinking process within the paper production causes non-methane volatile organic compound emissions to air (76.8% of the category impact) released from electricity generation. Human toxicity effects (carcinogenic and noncarcinogenic) derived from the first stage of the whole process are dominated by releases of hydrocarbons aromatic (70.8% of the total impact) generated during the bleaching process in the production of the thermomechanical pulp. Furthermore, dioxin emissions, attributable to paper disposal to municipal incineration, strongly contribute to this impact category. Major noncarcinogenic effects are wreaked by heavy metal emissions to water and soil: direct arsenic emissions to water is related to the ash disposal from deinking sludge to residual material landfill, while the zinc to soil emission is generated by the agricultural production of additives (potato starch) used in the paper production. The paper production phase causes the largest effect on ecotoxicity results compared with the printing and the disposal phase. Aluminum emissions released to soil and air, related to the consumption of hard coal and natural gas in energy supply processes, contribute significantly to the aquatic ecotoxicity category (69% of the category impact). The emissions of zinc released from agricultural production of auxiliaries contribute with 50.6% to the total category impact. In agreement with the other impact categories, ionizing radiation and ozone depletion are both dominated by the paper production stage. Radon (Rn222) and carbon (C14) emissions to air (64.1 and 30.9%, respectively) originating from electricity generation have the most relevant contribution to the ionizing radiation category. Releases of Halon 1211 and Halon 1301 in air attributable to gas transportation processes and to offshore natural gas and oil production dominate the ozone depletion category. Results were reported for both terrestrial and aquatic acidification potential. In the present scenario, paper production is the most important contributor to the overall acidification potential, which is mainly due to the release of NO_x, SO_2, and ammonia emissions to air from on-site energy production and for the agricultural production of additives (potato starch) used in the pulp production. The greatest contribution to the eutrophication potential comes from the pulp production stage, mainly as a result of COD

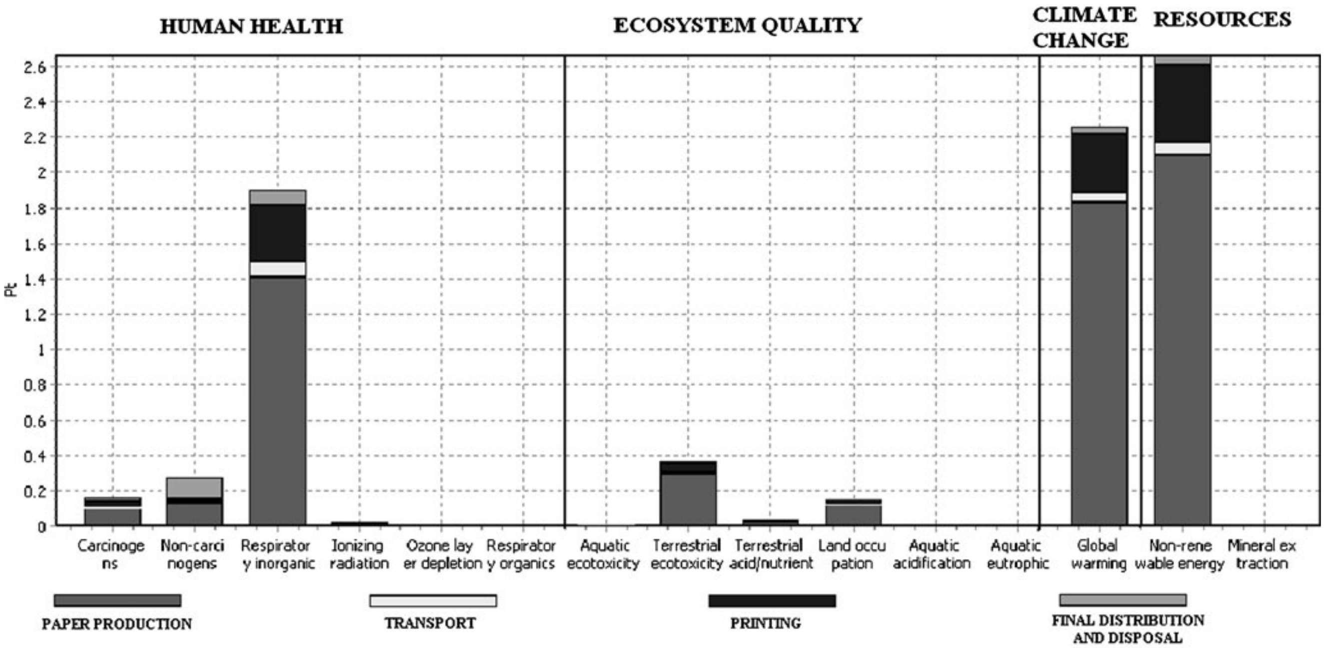

Fig. 2 Evaluation by impact categories related to the biweekly production of advertising folders. The impact categories are grouped according to damage categories

emissions to water (75.8%). The paper production stage has also a contribution to this impact category mainly due to phosphate emissions in water (12.8%) from agrochemical production. The largest contribution to land use comes from the soils occupied by: (a) potato field during the mulch process (57.4%) necessary to obtain the potato starch used in the pulp production stage, (b) walnut cultivation (19.4%) to produce chemical additives (rosin) used in the paper production phase; and (c) forest cultivation (11.2%) to obtain the fibers contained in the chipboard pallets. Paper production is the subsystem contributing most to mineral extraction which is dominated by releases of nickel (49.8%) and aluminum in ground (38.8%) from the manufacture of machinery and infrastructure components of the integrated paper mill.

3.2 Environmental results and considerations

The results of the analysis, reported in Fig. 2, show that the damage to human health is due to the effects of inorganic emissions (80.92%) caused by NO_x, particulates, and SO_2 emissions (27.24, 21.07, and 18.26%, respectively, of the total damage category) during the paper production stage. The effects on terrestrial ecotoxicity control overall ecosystem quality (66.58%). In this category, the damage is mainly due to zinc emissions on soil (33.72%), land occupation for agricultural production (15.59%), and aluminum in air (10.29%). The damage to climate change is generated by the emissions of 22,390 kg $CO_{2\ (eq)}$ due to paper production (81.19%), printing (14.24%), transport (2.62%), and distribution and disposal (1.95%). In the resources category, the energy-intensive operations in the paper production greatly contribute to the depletion of nonrenewable energy resources (99.91%). The consumption of natural gas (41.55%), crude oil (21.81%), uranium (16.16%), and hard coal (13.90%) in energy supply processes affects this impact category. Single score derived from the aggregation of the previous damages is 7.83 Pt for a weekly production of advertising folders (Table 4). The damage is due for 34.04% to resources, 30.03% to human health,

Table 4 Characterization and evaluation of the life cycle

Advertising folder life cycle	182,200 advertising folders (biweekly prints)
Human health (DALY)	1.67×10^{-2}
Ecosystem quality (PDF m^2 year)	7.57×10^{3}
Climate change (kg $CO_{2\ (eq)}$)	22,390
Resources ($MJ_{surplus}$)	4.05×10^{5}
Single score (Pt)	7.83

Table 5 Composition of the different papers used in the advertising folders production

	A	B	C
Grammage (g/m^2)	49	40	45
Recycled pulp (%)	74	31	60
Mechanical pulp (%)	2	58	30
Humidity (%)	5	8	9
Pigments and fillers (%)	19	3	1

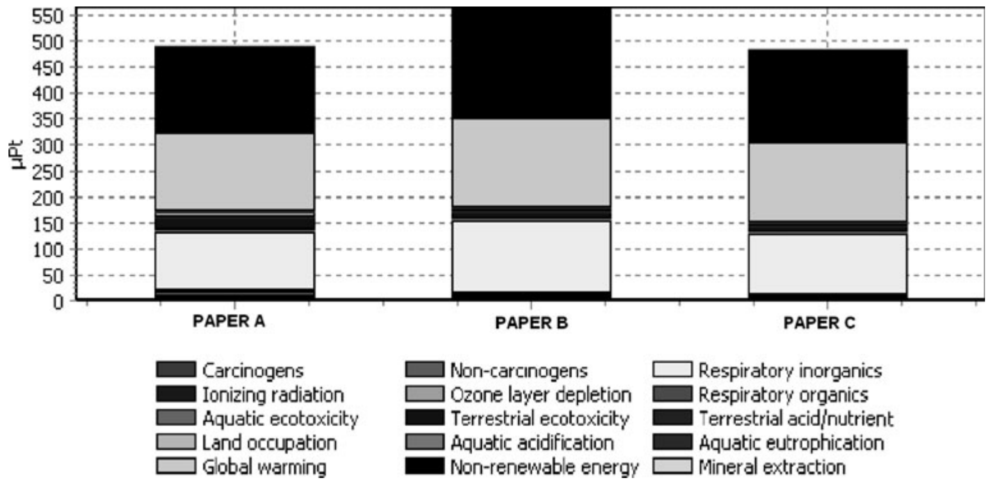

Fig. 3 Comparison of environmental impact values (Pt) for different papers

28.88% to climate change, and for 7.05% to ecosystem quality. Paper production is the process mainly responsible of the total damage (76.93%) together with printing (15.43%), while transport, distribution, and disposal play the minor role (3.04 and 4.60%, respectively). The main operations which generate the major impact in the paper production stage are related to the direct or indirect fossil energy use, the production of potato starch and rosin additives for bleaching operations, and the collection and selection of waste paper. Printing causes relevant impacts for the electricity and ink production and for the aluminum plates used in the offset printing.

To complete the environmental impact evaluation of the considered advertising folder production, a comparison between paper A and two papers, B and C, that mainly differ for percentages of mechanical and recycled pulp, was performed. The composition and the grammage of the different papers are reported in Table 5. The analysis was firstly conducted by comparing the different papers with the same weight. Figure 3 shows that paper B causes the major impact due to the highest content of mechanical pulp (5.63×10^{-4} Pt), while paper C leads to a decrease of the overall potential damage of 13.94% due to the largest amount of recycled fibers and the almost total absence of additives. Finally, a comparative life cycle analysis was made for a biweekly production of advertising produced with these different papers. Table 6 and Fig. 4 report the results for each damage category.

The advertising folders, the ones that produced paper B, generated the highest environmental load due to the significant impact of paper production and transport phases even though they have the lowest grammage. The use of paper C reduces the overall environmental burden of the whole cycle because of the damage reduction in the paper production stage. The difference in the results of kilograms of CO_2-equivalents calculated with IPCC and IMPACT 2002+ for the different papers is mainly due to the fact that IPCC takes into account the biogenic origin of CO_2 emissions offset by the absorption of CO_2 by plants. The major GWP value for advertising folders made with paper A depends on the little amount of mechanical pulp (2%) which slightly contributes to the absorption of CO_2. Consequently, the highest amount of mechanical pulp in paper B (58%) is responsible of the lower GWP.

4 Carbon emissions offset

Nowadays, product life cycle carbon footprints or GHG emissions inventories are increasingly being used by the companies to communicate to the consumers the potential contribution of a product to climate change and to take supply chain decisions for carbon offsets. Since 1990 until now, the amount of carbon dioxide emissions are continuously increasing due to human

Table 6 Characterization and evaluation of the life cycle of advertising folders obtained with different papers

182,200 advertising folders (biweekly prints)	Paper A	Paper B	Paper C
Human health (DALY)	1.67×10^{-2}	1.64×10^{-2}	1.50×10^{-2}
Ecosystem quality (PDF m^2 year)	7.57×10^{3}	5.46×10^{3}	4.12×10^{3}
Climate change (kg $CO_{2\ (eq)}$)	22,390	22,936	20,979
Resources ($MJ_{surplus}$)	4.05×10^{5}	4.36×10^{5}	3.91×10^{5}
Single score (Pt)	7.83	7.89	7.10
Global warming potential (kg $CO_{2\ (eq)}$)a	30,952	21,454	24,704

[a]IPCC 100 years

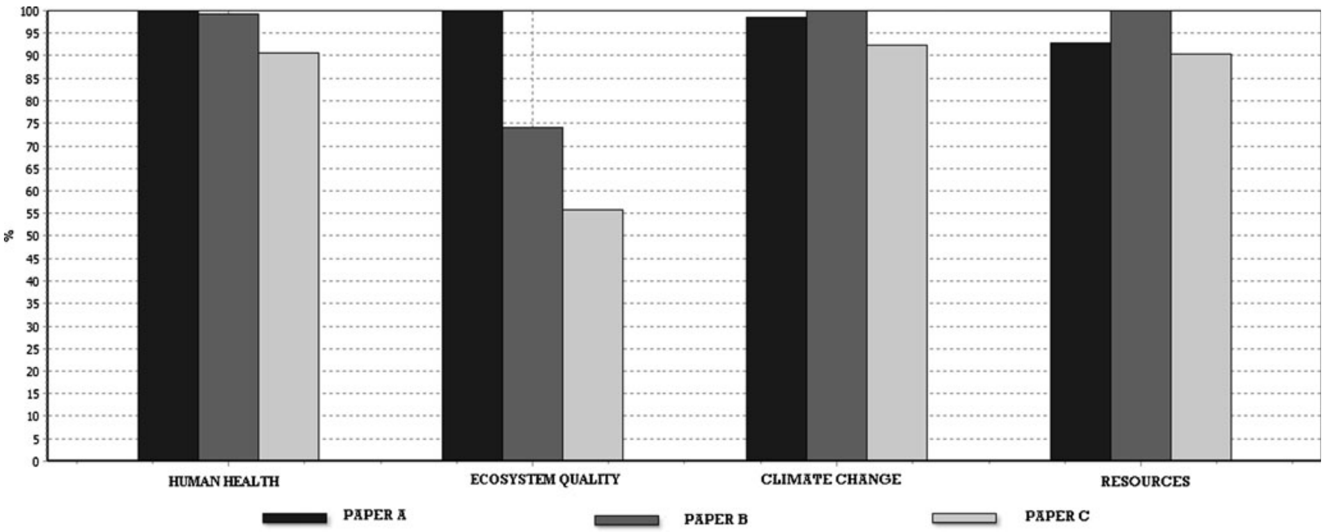

Fig. 4 Evaluation by damage categories related to the biweekly production of advertising folders obtained with different papers

activities, such as industry, pollution mitigation, combustion, or deforestation. The results of this study were used in order to make a preliminary quantification of the number of trees to be replaced for offsetting the mass of GHG emitted during the entire life cycle of advertising folders. In this case, softwood pulp was used to produce mechanical pulp. Data from the Ecoinvent database reported that the quantity of CO_2-equivalents absorbed by 1 m^3 of softwood corresponds to 897 kg/m^3 (Q_a) and the volume of a 120-year-old softwood tree (33.2 m height and 0.37 m diameter) amounts to 3.493 m^3 (V_a). In order to calculate the number of trees to be replaced for offsetting the emissions due to the production of advertising folders, the total amount of CO_2-equivalents was divided by Q_a and this result which represents the total volume of wood was divided by V_a (Table 7).

5 Conclusions and recommendations

Based on the inventory analysis and impact assessment results, the hot spots over the whole life cycle of advertising folders were identified and the following conclusions were drawn with respect to the considered system:

- The phases of the life cycle with the highest burdens are paper production (76.93%) and printing (15.43%), while the remaining processes do not give significant contributions.
- The most critical impact categories in the advertising folders life cycle are nonrenewable energy for fossil fuel consumptions, global warming, and inorganic emissions for NO_x, SO_2, and particulates emissions. These important environmental impacts are the results of the energy requirements especially in the paper production processes, which are realized by the consumption of electricity from the national grid mostly based on fossil fuels.
- Paper composition greatly affects the environmental impact of the advertising folders' life cycle. Though a paper with a low grammage is considered, as the content of mechanical pulp increases, the total impact increases as well. The use of a paper with a relevant content of recycled fibers and small amount of additives produce a reduction of the total damage of 13.94%. Furthermore, higher amounts of recycled fibers decrease the environmental burden caused by bleaching operations in the printing stage.
- The major global warming potential value for advertising folders made with paper A depends on the little amount of mechanical pulp (2%) which slightly contributes to the absorption of CO_2.
- Better environmental performance can be reached by improving the efficiency of the technology in the paper production and printing stage in order to save energy. In particular, the benefits of renewable energy source should be explored.
- In the disposal stage, energy recovery was not considered. Different disposal scenario and energy recovery can be also considered to show the best environmental profile for handling waste.
- It is necessary to highlight that much scientific uncertainty surrounds the precise quantification of carbon

Table 7 CO_2-equivalent emission offset

	Paper A	Paper B	Paper C
kg $CO_{2\ (eq)}$	30,952	21,454	24,704
Number of trees	9.88	6.85	7.88

sequestered in trees and soils (Paustian et al. 2000). An accurate carbon inventory, taking into account the potential land area, should be performed in order to quantify the net carbon benefit of planting a tree.

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